MAN–MADE RADIO EMISSIONS RECORDED BY CASSINI/RPWS DURING EARTH FLYBY

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Abstract

In the days around closest approach of the Cassini spacecraft to Earth at August 18, 1999, the electromagnetic spectrum measured by the RPWS (Radio and Plasma Wave Science) instrument in the range above 1 MHz is dominated by intense emissions at fixed frequencies. We investigate the appearance and characteristics of these signals and show that most of them can be attributed to terrestrial shortwave radio bands. Interestingly, there is a relatively "quiet" period for about 20 minutes right before closest approach, which can be well explained as an ionospheric shielding effect and by the fact that radio stations are practically absent over the Southern Pacific region over which the s/c traverses in this short period.

1 Introduction

The primary goals of RPWS observations at Earth were (1) to validate the wave normal analysis capability [Hospodarsky et al., 2001], and (2) to perform direction–finding of AKR (Auroral Kilometric Radiation) as a preparation for the antenna calibration at Jupiter. Besides man–made emissions natural radio and plasma waves like AKR, upper hybrid waves, electron cyclotron harmonic waves, and waves due to Earth bowshock– and magnetopause–crossings were recorded [Kurth et al., 2001]. Within ±14 Earth radii radio emissions from terrestrial lightning were found [Gurnett et al., 2001], which were not so easy to identify due to the massive interference from man–made radio emissions.

2 Geometry of the Cassini/Huygens Earth flyby

The geometry of the Earth flyby can be seen in Figure 1: The s/c approached our planet from about 13:00 LT (local time), traversed quickly over the Southern Pacific region, where the closest approach (CLA) took place at 03:28:30 SCET at an altitude of 1186 km near 19:00 LT at a latitude of 23° South, and finally it flew away on the nightside of the Earth over South America. The s/c performed a gravity assisted flyby and passed the Earth on its trailing side (evening side) to gain kinetic energy.

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The speed of the s/c was approximately 16 km s^{-1} during inbound and outbound, and had a maximum of about 19 km s^{-1} at CLA.

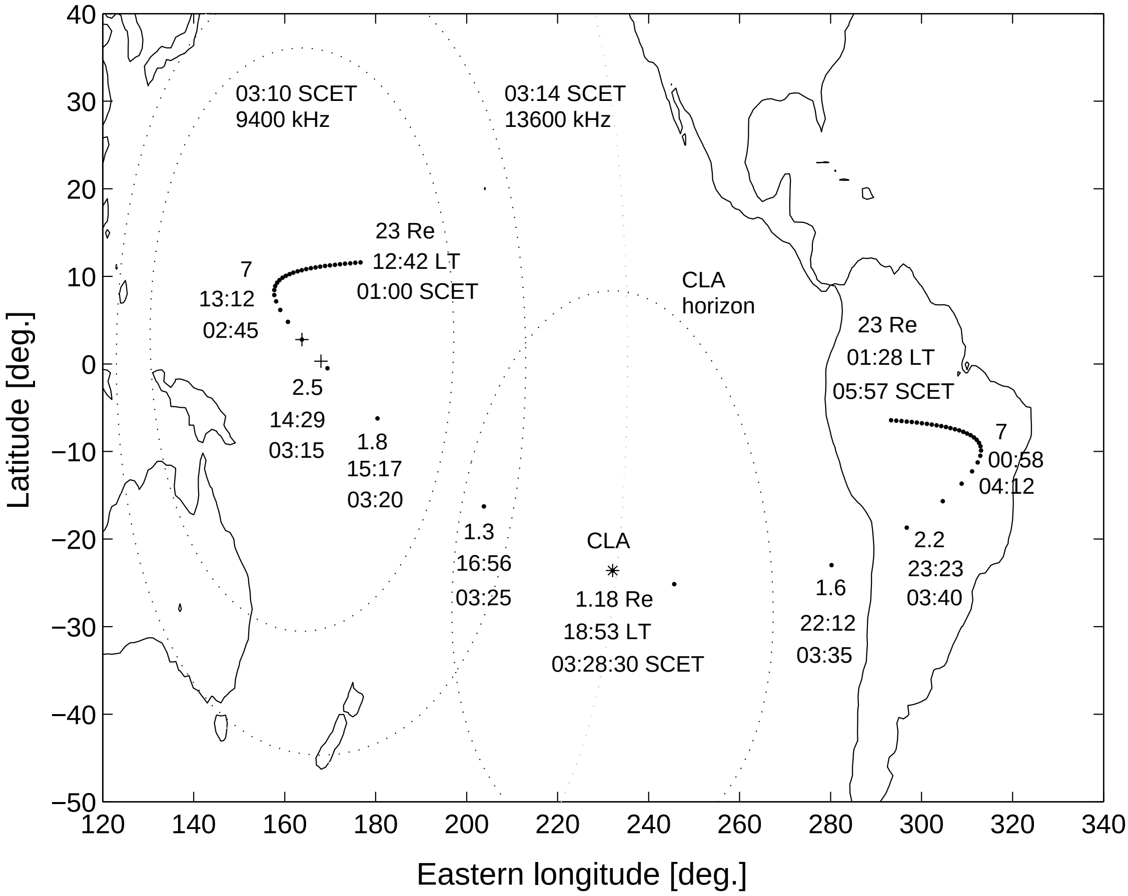

Figure 1: Foot points of the Cassini/Huygens trajectory on the surface of the Earth during the flyby on August 18 (DOY 230), 1999, from 01:00 to 06:00 SCET (every 5 minutes). Numbers denote the distance of the s/c to the center of the Earth in Earth radii, the local time at the respective point of the Earth, and the SCET. The CLA at 03:28:30 SCET is marked by a star, and the three dotted circles correspond to ground ranges at various times and frequencies, which is explained in section 4.

The RPWS instrument was powered on at August 13 (DOY 225) and powered off at September 4 (DOY 257), 1999. The H2 part of the HFR (High Frequency Receiver) was in the following modes around the days of closest approach: from power–on until 05:23 SCET, DOY 230, H2 was used in the dipole mode with frequency steps of 200 kHz sweeping from 1825 to 16025 kHz with an integration time of 20 ms. Afterwards until 06:30 SCET, DOY 237, the direction finding mode (switching monopoles) was used with an integration time of 80 ms and 200 kHz steps from 4025 to 16025 kHz.

3 Man–made radio emissions

Terrestrial radio stations were detected easily by the RPWS above the ionospheric cutoff frequency (7–8 MHz at the dayside, 1–2 MHz at the nightside, see Figures 2 and 3). The bandwidth of the HFR is 25 kHz, and as shortwave broadcasting stations are typically spaced 5 kHz or closer, the resulting signal is the summation of all these stations [Kaiser et al., 1996; Passport to World Band Radio, 1998].

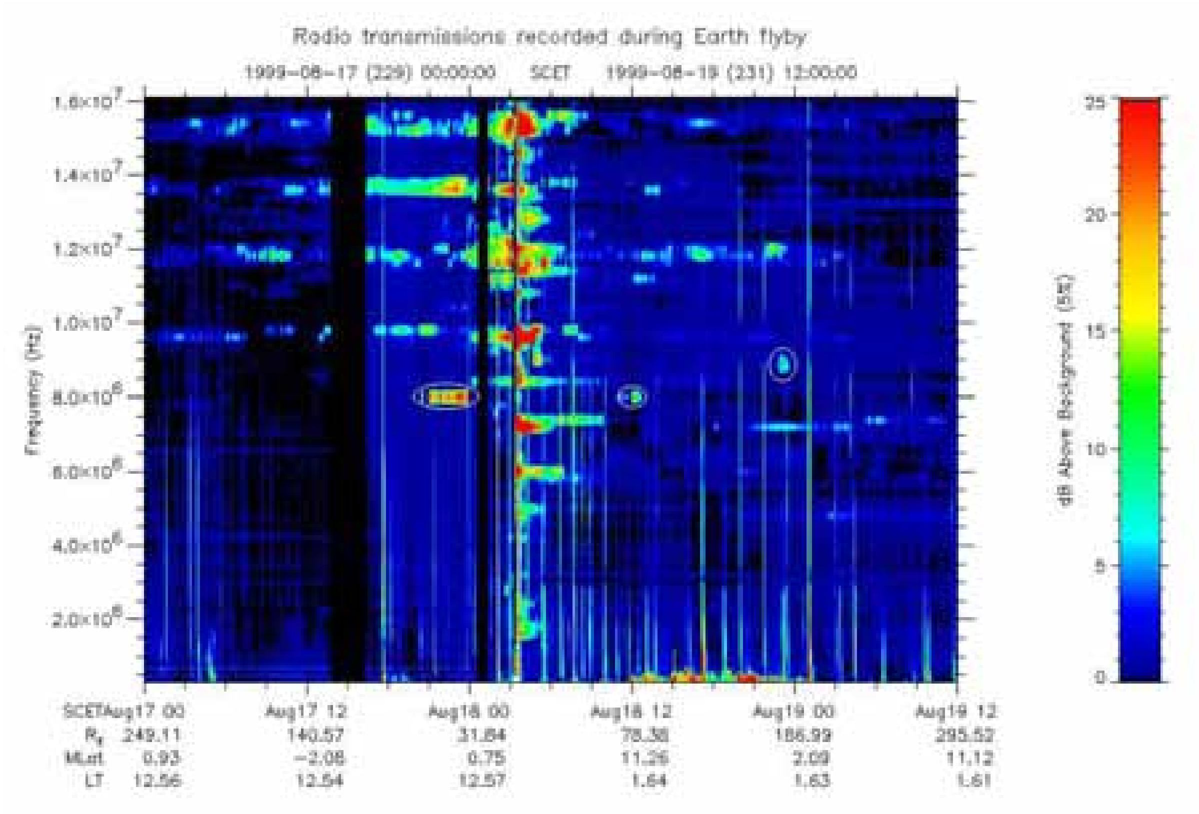

Figure 2: Dynamic spectrum over $2\frac{1}{2}$ days showing mainly the man–made radio transmissions at fixed frequencies. The two encircled emissions at 8025 kHz (Aug. 17 21:00 to 24:00, and Aug. 18 12:15) are the signals from the HAARP (High-frequency Active Auroral Research Program) facility in Alaska, and the one at 9025 kHz (Aug. 18 23:15) is from the Russian SURA near Nizhny Novgorod [Tokarev et al., 2005].

As can be seen in Figures 1 and 2 and listed in the table, with Cassini approaching from the dayside mainly the Asian and Australian radio stations in the 19, 22, 25, and 31 m bands were “audible”, whereas after closest approach and due to the drop of the ionospheric cutoff also the 41, 49, 60, and 120 m bands got “audible”, but now originating from South American radio stations. Careful inspection of Figure 3 shows that different frequencies within the various bands are occupied at Cassini inbound compared to outbound: For example at inbound there were fixed–frequency emissions at 12225 kHz in the 25 m band, which were absent at outbound, and similarly in the 31 m band at 9825 kHz there were very strong emissions at outbound from the South American radio stations, whereas there

Table 1: Appearance and characteristics of man-made signals recorded by Cassini RPWS from 01:33 to 05:23 SCET (DOY 230, 1999) during Earth flyby. All times in this table are SCETs. CLA stands for closest approach of the spacecraft occurring at 03:28 SCET.

Frequency [kHz]	Remarks on signal strength and appearance	Possible source
1625 1825 2025, 2225	weak signals only after CLA weak signals only after CLA weak signals only after CLA from 03:30 to 04:18	AM radio broadcast 160 m amateur band Fixed, mobile, and maritime moblile
2425	weak signals only after CLA for a short time	120 m band 2300–2500 kHz
2625, 2825	weak and sporadic signals from 03:30 to 03:53 and after 02:05 before CLA for 2825 kHz	Fixed, mobile, and maritime mobile
3225	nearly no signal	90 m shortwave band 3200–3400 kHz
4025	no signal	75 m shortwave band 3900–4080 kHz
4225	weak signals from 02:55 to 03:11	Maritime mobile
4825, 5025	signals after CLA starting at 03:31	60 m shortwave band 4700–5100 kHz
5425, 5625	weak signals after CLA from 03:31 to 03:45	Fixed, mobile, and aeronautical mobile
5825, 6025	strong at 6025 kHz, weak signal at 5825 kHz after CLA starting at 03:30	49 m shortwave band 5730–6250 kHz
6425 7025	weak signals after CLA from 03:32 to 03:58 weak signals from 01:50 to 02:40	Maritime mobile 40 m amateur CW
7225, 7425	strong signals only after CLA from 03:30	41 m shortwave band 7100–7600 kHz
7825 8025 8425 8625, 8825, 9025 9225	weak signals before CLA (01:30 to 02:55) weak, sporadic signals from 02:55 to 04:10 strong signals, pause from 03:05 to 03:30 signals mainly after CLA weak signals at various times (01:30 to 02:15, 03:30 to 04:02, and 04:43 to 05:23)	Fixed, mobile Fixed, mobile Space Research freq. allocation Maritime and aeronautical mobile Fixed freq.
9425, 9625, 9825	very strong signals, pause from 03:03 to 03:28, strongest at 9625 kHz	31 m shortwave band 9250–10000 kHz
10825 11025, 11225 11425	signals after CLA from 03:32 to 05:23 signals mainly before CLA from 01:33 to 03:17 (sporadically after CLA) strong signals only after CLA, from 03:32 to 05:23	Fixed, mobile Fixed, mobile, and aeronautical mobile Fixed freq.

Table 2: Continuation of Table 1.

Frequency [kHz]	Remarks on signal strength and appearance	Possible source
11625, 11825, 12025	strong signals, pause from 03:13 to 03:25	25 m shortwave band 11500–12160 kHz
12225, 12425	signals only before CLA until 03:09	Fixed freq.
12625	weak signals from 01:33 to 04:40	Maritime mobile
12825, 13025	weak signals from 03:32 to 05:23, and from 01:33 to 02:15 at 13025 kHz	Maritime mobile
13625	strong signals with pause from 03:14 to 03:32	22 m shortwave band 13570–13870 kHz
14025	sporadic signals from 01:40 to 04:52	Amateur CW
14425, 14625	weak signals from 01:33 to 03:17 (14425 kHz), and 03:30 to 05:23 (at 14625 kHz)	Fixed, mobile
14825, 15025	sporadic signals from 01:33 to 03:18	Fixed freq. and aircraft band
15225, 15425, 15625	very strong signals, at 15225 kHz and 15425 kHz also present at CLA	19 m shortwave band 15000–15800 kHz
16025	signals from 02:15 to 03:15	Fixed freq.

were no emissions at the same frequency at inbound. In the 90 and 75 m bands there were nearly no signals, and as can be seen in the table other emissions can be attributed to various fixed and mobile frequencies. All maritime mobile frequency bands located at 2000–2107 kHz, 2170–2194 kHz, 4000–4438 kHz, 6200–6525 kHz, 8100–8815 kHz, and 12230–13200 kHz (according to the US National Telecommunications and Information Administration NTIA) showed some emissions. At inbound the first weak signals of radio stations appeared at DOY 228 at 00:00 in the 19 m band, whereas at outbound the last emissions were at DOY 233 at 06:00 in the 41 m band, when Cassini was in a distance of approx. 675 Earth radii.

4 The ionospheric "iris" effect

The "quiet" period of about 20 minutes (clearly seen in Figure 3) can be explained by a shielding ("iris") effect of the ionosphere and by the fact that radio signals are rare in the Southern Pacific region. It was shown by Herman et al. [1973] that the maximum ground range R from the subsatellite point to a point source observable by the satellite depends upon the ratio of the observing frequency f to the ionospheric critical frequency f_0 in the F2 layer in the following way:

$$\left(\frac{f_0}{f}\right)^2 = 1 - R_E^2\left(\frac{R_E + h_S}{R_E + h_I}\right)^2 \frac{\sin^2(\frac{R}{R_E})}{R_E^2 + (R_E + h_S)^2 - 2R_E(R_E + h_S)\cos(\frac{R}{R_E})} \qquad (1)$$

with R_E as the radius of the Earth, h_S as the height of the s/c, and $h_I = 300$ km as the height of the ionospheric F2 layer. This formula results from the fact that with a rising angle of incidence the frequency being reflected by the ionosphere is also increasing. Figure

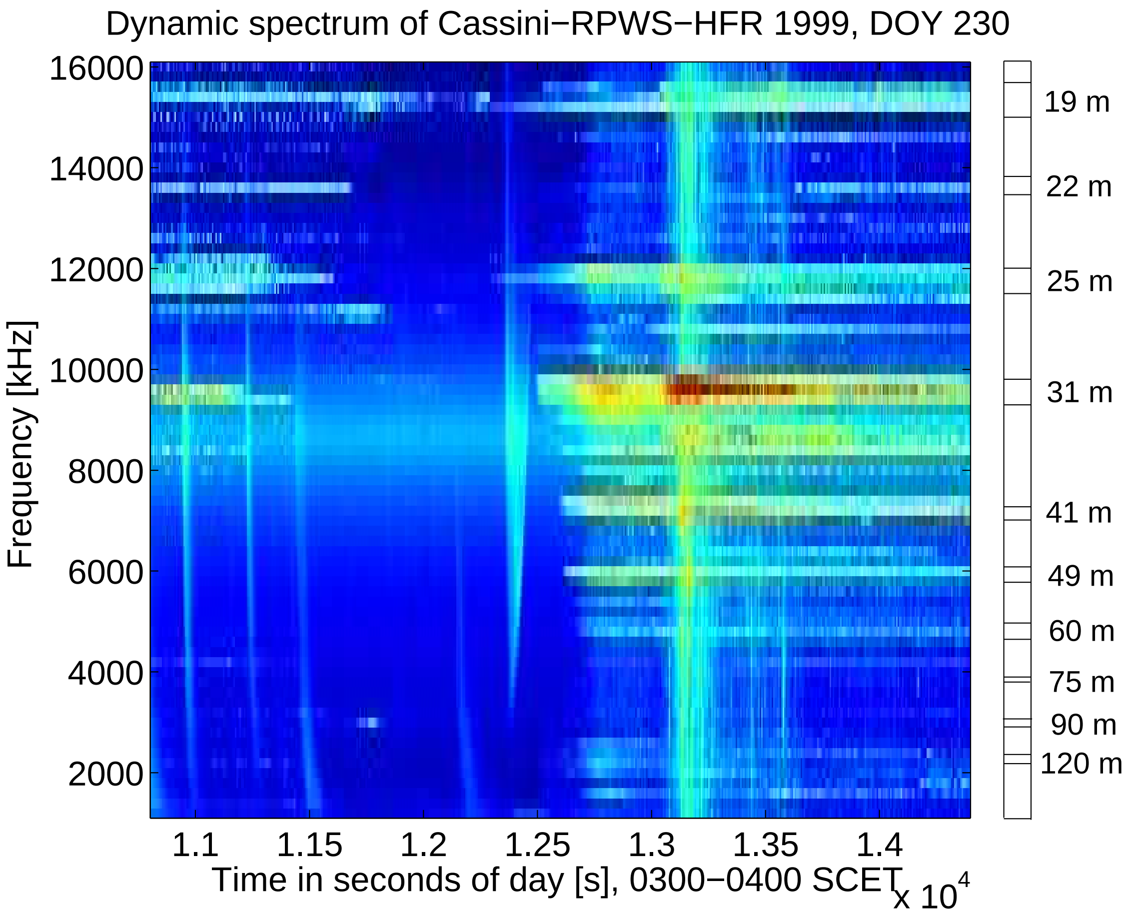

Figure 3: Dynamic spectrum from 03:00 to 04:00 SCET, DOY 230, around closest approach (03:28, 12500 seconds of day) to Earth. The "quiet" period can be clearly seen and the bar on the right side indicates that most emissions are due to shortwave radio stations. The intensity scale goes from 0 (blue) to 60 dB (red) above background.

4 shows this ground range R, which was calculated for the Cassini inbound trajectory using a critical freq. $f_0 = 7000$ kHz. Additionally the ground range for no ionospheric shielding is drawn in Figure 4. It is labelled as "horizon" (R_H), and it corresponds to the geometrical horizon of visibility, and one finds from a simple geometric consideration

$$R_H = R_E \arccos\left(\frac{R_E}{R_E + h_S}\right), \tag{2}$$

and R_H is the distance on the curved surface of the Earth from the foot point of the spacecraft to the point, where a tangent from the spacecraft hits the Earth. For a very distant spacecraft R_H comes close to a quarter of the circumference of the Earth, which is about 10000 km.

It can be seen in Figure 3, that when the s/c reached this "quiet" region, the radio stations with lower frequencies disappeared before those with higher frequencies. The 31 m shortwave band around 9400 kHz stopped at 03:10, where a ground range of 3710 km

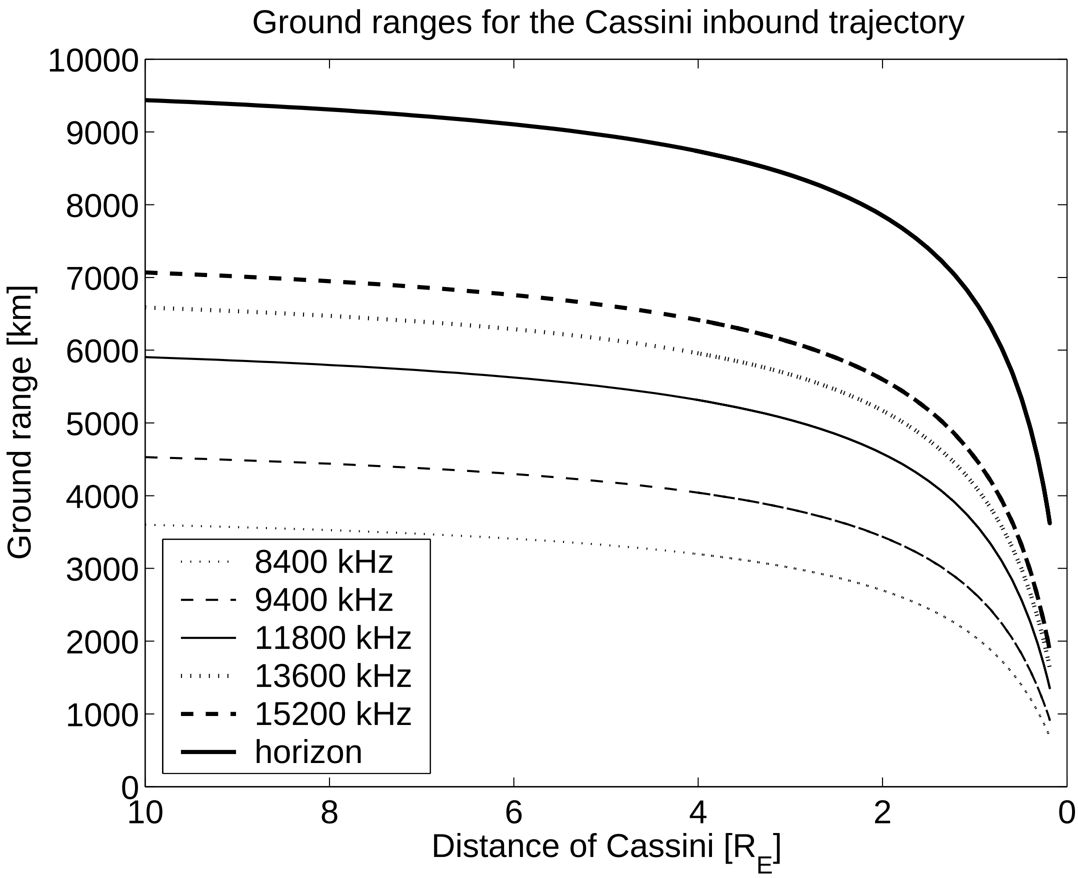

Figure 4: Ground range R as a function of s/c distance of Cassini from the surface of the Earth with the frequency as parameter for the inbound trajectory. The bold line labelled "horizon" corresponds to the optical horizon of visibility, which is evidently much greater than the field of view for radio waves. This shielding can be regarded as an "iris" whose diameter increases with increasing frequency. For the outbound trajectory the critical frequency is much lower (nightside) and the ground range comes close to the horizon of visibility.

was calculated, which corresponds approx. to the distance of Australia (Brisbane is 3560 km away). The circle with this ground range is drawn in Figure 1, which has this non–circular egg–like shape only due to the projection. The 25 and 22 m bands (11800 and 13600 kHz) stopped at 03:13 and 03:14 corresponding to ground ranges of 4530 and 5010 km, respectively, which is approx. the distance to Taiwan or Japan (Tokyo would be 4760 and 4900 km away), and there are no Australian stations in this frequency range as Australia would be still within the ground range [Passport to World Band Radio, 1998]. Also this ground range circle is drawn in Figure 1, and from Figure 4 it can be seen that the geometrical horizon at this time (03:14) and s/c position ($\approx$ 1.6 Earth radii from the surface) is about 7500 km. Consequently there must be such an ionospheric "iris" effect as there is a cessation of the signals, otherwise all the Asian radio stations should still be received. It has to be mentioned that the ground ranges are calculated for direct rays, whereas the actual ground range might be greater due to multiple ionospheric reflections or so-called Pedersen rays moving almost parallel to the Earth along the ionosphere. This might be the reason for the continuous coverage of the strong 19 m band throughout the quiet period. Interestingly at closest approach the s/c is in a height of 1186 km with a visible horizon of 3600 km (see again the circle in Figure 1), but strong signals from radio stations (especially the 31 m band) are already recorded, although South America is still in a distance of 6000 km, and the changing ionospheric conditions (s/c goes to the nightside) and the mentioned mechanisms must be responsible to enlarge the "radio horizon". On the other hand a strong onset of lightning activity occurs only 5 minutes later at 03:33, when the geometrical horizon is around 4700 km, which corresponds quite well to the distance of the South American tropics at that time (e.g. Brasilia is 4600 km away).

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